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With the funding from DURIP grant F 49620–95–1–0123 a total of seven workstations from Silicon Graphics Inc. and several peripherals and accessories, including a 36 GB disk array have been purchased. This equipment has been utilized effectively to perform pre– and post–processing tasks for our DOD funded research projects. The instrumentation is very well suited to perform our high needs of fast disk I/O in order to display time–dependent data for the post–processing. In addition, the multi–processor workstations have allowed us to develop and test our Navier–Stokes codes locally and improve their performance before performing production runs at the DOD High–Performance Computing Centers.

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DURIP Grant No. F 49620–95–1–0123

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Advanced Pre– and Post–Processing Eqipment for Time–Dependent Numerical Simulations of Complex Flows

by

Hermann F. Fasel

Abstract

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Equipment purchased with funding from DURIP grant F 49620–95–1–0123 :

Silicon Graphics Workstations **$367,846**

Graphics Workstation

[Power Onyx Reality Engine2 by Silicon Graphics Inc.]

Including:
- Power Onyx Reality Engine2 Deskside
- 2 R8000/90 CPUs w/ 4MB secondary cache
- 512 MB Memory
- 4 GB System Disk
- 4 GB Differential Disk
- 2 GB DAT Internal Drive
- 680 MB CD–ROM Drive
- FDDI Controller
- 21" MultiSync Monitor
- IRIX 5.3 System Software
- FORTRAN and C Compiler
- Program Development Option
- Network File System
- Installation

Two Power Challenge Workstations

[Power Challenge L by Silicon Graphics Inc.]

Including: Power Challenge L Deskside
4 R8000/90 CPUs w/ 4MB secondary cache
512 MB Memory
4 GB System Disk
4 GB Differential Disk
IRIX 5.3 System Software
Network File System
FDDI Controller
Installation

Power Indigo Graphics Workstation

[Power Indigo Extreme by Silicon Graphics Inc.]

Including: Power Indigo Extreme
1 R8000/75 CPU w/ 2MB secondary cache
128MB Memory
4 GB System Disk
8 GB Differential Disk
IRIX 5.3 System Software
Network File System
FDDI Controller
Installation

Three Indy Workstations

[Indy by Silicon Graphics Inc.]

Including: Indy
1 R5000/150 CPU
64MB Memory
1 GB System Disk
IRIX 5.3 System Software
Network File System
Installation

Peripherals and Accessories **$ 7,642**

Macintosh Computer

[PowerMac Performa and printer by Apple Computer, MacWarehouse]

Hard Disk Array

[36 GB Hard Disk Array Striped for Optimal Performance
by Nordisk, Four Corners, Falcon]

Including: Fast Wide Differential SCSI-2 Host Adapter
9 Seagate Barracuda 4 GB SCSI Drives
Host Controller SCSI Terminator
6' Wide Differential SCSI Cable

Accessories

[Graybar, UA Stores, Crescent Electric, MacWarehouse, Laser Experts]

Including: FDDI Cable
Computer Cable
Printer Cartridges
Data Tapes

TOTAL COST **$375,488**

University of Arizona Cost Sharing **$ 75,097**

DOD COST **$300,391**

Summaries of Research Projects for which Equipment Was Used

DOD Agency: Air Force Office of Scientific Research
Contract Number: F49620–94–1–0208 (Dr. James McMichael)
Title: **Numerical Simulations of Wall Jets**
Principal Investigator: H. Fasel
Duration: March 15, 1994–March 14, 1997
Amount: $189,790

Wall jets, or wall–jet–like flows, are of great technical relevance for numerous aerospace applications. Wall jets can be used as efficient means of controlling external and internal boundary layers. For external applications, wall jets can be employed advantageously for circulation control of airfoils and thus can serve as efficient lift–augmentation devices. Such lift augmentation can be accomplished by either tangential blowing (through the wing section) along the upper surface of airplane wings or by employing multi–segment airfoils (for example, slotted flaps). Wall jets are also highly relevant for modern jet engines, where wall jets occur, for example, in the flow over a cowl of a fan–jet engine or, internally, in the flow over film–cooled turbine blades.

In spite of the great technical importance of wall–jet flows, relatively little is known about transitional and turbulent wall jets. This is due to the complicated physics involving the evolution and interaction of large (coherent) structures. From experimental evidence, it is known that the large structures dominate the flow behavior. In particular, the behavior of the structures appears to be controlled by nonlinear effects, which makes theoretical investigations very difficult. Experiments are also difficult and costly to perform. Therefore, in this research project, Direct Numerical Simulations (DNS) and Large–Eddy Simulations (LES) are employed, with the goal of understanding the fundamental mechanisms that power the dynamic behavior of the large structures. With that knowledge, chances are much higher of finding strategies to favorably control these flows, namely, by manipulating the large structures. Toward this end, numerical methods for solving the complete Navier–Stokes equations for incompressible flows have been developed that are tailored for efficient simulations of wall jets. The numerical codes developed for this purpose employ highly accurate, compact, finite difference approximations in the downstream and wall–normal directions while using pseudospectral approximations in the spanwise direction. It is important to note that the underlying numerical model is "spatial," thus allowing realistic spatially developing flow simulations. In this research project we are at a stage where preliminary direct simulations are being carried out and, therefore, the enhanced post–processing capability of the aquired equipment has been of great help. The high–performance workstations have been absolutely essential for truly scrutinizing the data of thefull–scale simulations. The codes for the LES are still in development and the pre–processing support from the workstations have considerably shortened the code development time.

DOD Agency: Air Force Office of Scientific Research
Contract Number: F49620–94–1–0131 (Dr. James McMichael)
Title: **Film Cooling by a Pulsating Wall Jet: Experiments, Numerical Simulation, and Stability Theory**
Principal Investigators: I. Wygnanski, A. Ortega, and H. Fasel
Duration: January 15, 1994–January 14, 1997
Amount: $469,018

Wall jets have both a fundamental and practical significance in convective heat transfer. In the presence of a free stream, tangential blowing near a solid surface, a wall jet, is widely used for film cooling applications, such as film–cooled gas turbine blades, combustion chambers, exhaust nozzles of rockets, etc. On the other hand, a heated wall jet can be used to prevent icing of airplanes or to de–ice them.There has been considerable interest in film–cooling (–heating) using wall jets. However, as evidenced by the extensive research literature, many fundamental issues regarding the efficiency of wall jets are not yet understood. We do know that the large (coherent) structures of turbulent wall jets play a decisive role in the heat transfer mechanism, and thus the usefulness of wall jets for film cooling. From our past research at

The University of Arizona, we also know that the evolutionary and dynamical behavior of the large structures can be influenced by controlled, time-dependent forcing. For example, for a "cold" wall jet blown over a curved surface, periodic pulsing of the wall jet (even with every small amplitudes) increases the region where the flow stays attached to the wall before separation sets in. In addition, due to nonlinear effects, the wall jet organizes the structures in such a way that the mean skin friction is reduced. Considering the effects that pulsing has on the dynamical behavior of the wall jet, the effect on heat transfer might turn out to be even more striking and might lead to new knowledge that could have considerable impact on airplane design and development.

Because of the considerable importance of unsteady pulsating wall jets, an extensive numerical-experimental research program was initiated at The University of Arizona. In parallel with experimental investigations, Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) have been carried out that allowed direct comparison of numerical and experimental results. Toward this end, we have developed numerical methods for solving the complete Navier-Stokes equations for compressible flows, although at first only incompressible (low subsonic) applications are being considered. Using the compressible equations allows for total coupling of all temperature effects with fluid dynamical effects, such as temperature-dependent density, viscosity, etc.

DOD Agency: Army Research Office
Contract Number: DAAL03-92-G-0228 (Dr. Thomas Doligalski)
Title: **Numerical Investigation of Transitional and Turbulent Axisymmetric Wakes at Supersonic Speeds**
Principal Investigator: H. Fasel
Duration: May 1, 1992-April 30, 1995
Amount: $440,174

A comprehensive effort is being undertaken to investigate transitional and turbulent axisymmetric wakes behind cylindrical bodies aligned with the flow at supersonic speeds. Particular emphasis is on identifying and understanding the dynamical behavior of the large-scale vortical structures that control the flow behavior in a supersonic wake. Direct Numerical Simulations (DNS) and Large-Eddy Simulations (LES) are the main investigative tools. The numerical simulations are supported and complemented by a theoretical effort based on stability theory analysis and Proper Orthogonal Decomposition (POD) techniques, which are applied to the numerically generated data.

For axisymmetric aerodynamic bodies in supersonic flight, the flow field in the wake region has considerable effect on the aerodynamic drag. Even small changes in the flow behavior of the wake may affect the performance of the entire flight vehicle, e.g., missiles, rockets, or projectiles. The effect on the aerodynamic drag is mainly due to the recirculation region that develops in the base region of the body and thus to the low pressure associated with the recirculating flow ("base drag"). Flight tests with projectiles (U.S. Army 549 projectile) have shown that the base drag may account for up to 35% of the total drag. This suggests that attempts to modify the near-wake flow such that the base pressure would increase could be highly rewarding with respect to drag reduction and, as a consequence, with regard to increasing the performance characteristics of flight vehicles or projectiles.

It is well known that for subsonic (incompressible) wakes, the dynamics of the large (coherent) structures play a dominant role in the local and global behavior of the flow. This evidence was found from both experimental investigations and numerical simulations (including ours) and was confirmed by theoretical studies. For supersonic speeds, on the other hand, very little is yet known about the dynamical behavior of turbulent flows. This is true for supersonic flows in general and for axisymmetric wakes in particular.

Thus, the question arises: Do large structures play a similarly important role for supersonic separated flows and in particular for supersonic axisymmetric wakes? There are few experimental investigations that have focused on this issue. However, when looking at flow visualization pictures of supersonic wake flows, distinct patterns with large-scale structures can be observed. For supersonic axisymmetric wakes, the mean flow structure of the near-wake region is characterized by the axisymmetric shear layer originating at the sharp corners of the blunt base.

Supersonic axisymmetric wakes are extremely difficult to investigate experimentally. Wind tunnel

interference and interference from model support strongly affect the mean flow behavior, which may be an indication that this behavior might be caused by the presence of large coherent structures. Because of the experimental difficulties, numerical simulations represent a new alternative for investigating the complicated unsteady flow phenomena in the supersonic wake.

Direct numerical simulations using the complete Navier–Stokes equations are restricted to somewhat low–to–moderate Reynolds numbers because of the rapidly increasing demands on computing power as the Reynolds number increases. Therefore in the course of this research, we have been working on ways to drastically increase the algorithmic efficiency of our Navier–Stokes codes. We have found that our basic codes require relatively little overhead costs when run on parallel machines.

Because of the Reynolds number limitations on direct simulations, we have also performed Large–Eddy Simulations (LES) using subgrid–scale turbulence models. Because our Navier–Stokes equations are highly suited for implementation of subgrid–scale turbulence models, we are able to use essentially identical codes for both the direct and large–eddy simulations. This allows proper fine–tuning of the LES codes (in particular, of the subgrid–scale models) so that they can be applied with greater confidence to the higher Reynolds number calculations.

DOD Agency: Army Research Office
Contract Number: DAAH04–93–G–0393 (Dr. Thomas Doligalski)
Title: **Investigation of Coherent Structures in the Shear Layers of Supersonic Wakes**
Principal Investigator: H. Fasel
Duration: September 1, 1993–August 31, 1996
Amount: $83,000

This research is funded by the AASERT Program. The goal of these investigations is to contribute toward an understanding of the fundamental mechanisms that are responsible for the evolution and dynamical behavior of the coherent structures in the shear layers of a supersonic wake. The detailed investigation of the dynamical behavior of the shear layers synergistically enhances the main study of the global dynamical behavior of supersonic axisymmetric wakes which is being carried out through funding from the parent grant, DAAL03–92–G–0228 (as summarized above).

For these investigations, we also employed Direct Numerical Simulations (DNS) and Large–Eddy Simulations (LES). Numerical methods and computer codes for such simulations were developed with funding from the parent grant. The numerical simulations were supported by theoretical investigations using both the classical stability theory and Parabolized Stability Equation (PSE) approach. In addition to investigations of axisymmetric shear layers, a major focus was placed on shear layers in a plane wake. This enabled detailed and rigorous comparison of the simulations to measurements from an experimental effort (for a plane shear layer) being conducted at The University of Illinois.

DOD Agency: Office of Naval Research
Contract Number: N00014–94–1–0095 (Dr. Patrick Purtell)
Title: **Effects of Adverse Pressure Gradient and Wall Curvature on the Turbulence Mechanisms in Boundary Layer Flows: Reynolds–Averaged Navier–Stokes Calculations, Large–Eddy Simulations, and Direct Numerical Simulations for the Stratford Ramp**
Principal Investigator: H. Fasel
Duration: October 1, 1993–September 30, 1996
Amount: $417,653

The main goal of this research project is to identify and understand the combined effects of strong adverse pressure gradient and strong streamwise curvature on the turbulence mechanisms of turbulent boundary layers at high Reynolds numbers. For these investigations, the so–called Stratford ramp was chosen as a generic flow geometry. For this geometry, both adverse pressure gradient and streamwise curvature act on the turbulent boundary layer in a unique way: the boundary layer is continuously on the verge of separation. This flow geometry was highly suited for our attempts to identify and understand the relevant turbulence mechanisms and, as a consequence, for developing better turbulence models for nonequilibrium

turbulent boundary layers. For these investigations, Reynolds–Averaged Navier–Stokes Calculations (RANS), Large–Eddy Simulations (LES), and Direct Numerical Simulations (DNS) were employed. Special focus was on performing computations for Reynolds number regimes where either LES and RANS or DNS and LES can be carried out simultaneously. The Direct Numerical Simulations are crucial to the LES effort, namely for developing improved subgrid–scale models. Post-processing numerical data [using diagnostic tools such as interactive time–dependent graphics, linear/nonlinear stability theory, parabolized stability equations (PSE), proper orthogonal decomposition (POD), etc.] obtained from the overlapping calculations will greatly enhance chances for identifying the relevant mechanisms, which then can be incorporated in improved turbulence models. In order to efficiently perform these post-processing tasks for the massive amount of time–dependent data generated by the simulations, the high–performance workstations have been vital to this project. The computational effort was conducted in direct and close collaboration with an experimental effort by I. Wygnanski (The University of Arizona) and a theoretical turbulence modeling effort by C. Speziale (Boston University). In addition, this group effort is linked to the computational effort by T. Huang (David Taylor Model Basin), who will test the improved Reynolds stress models that result from our investigations for Navy relevant geometries.

Summary of How the Aquired Instrumentation Has Enhanced the DOD–Funded Research

The instrumentation has significantly supported our DOD–funded research and, as a consequence, has enabled major progress in DOD–relevant Computational Fluid Dynamics research that would otherwise not have been possible. In particular, with the high–speed workstations aquired, we were able to close an existing gap that had prevented us from fully utilizing the massive computing power available to us at the DOD High–Performance Computing Centers and the NSF Supercomputer Centers. As summarized above, we were engaged in several DOD–sponsored research projects requiring highly challenging numerical simulations of complex flows that have never been attempted before. We were numerically simulating transitional and turbulent flow phenomena in a variety of flow geometries, such as wall jets (with and without heat transfer; funded by AFOSR), supersonic wakes (supported by ARO), and boundary layers along flat and curved walls (supported by ONR). In all cases, the flows considered were strongly time dependent and the phenomena to be investigated are highly nonlinear. Flow speeds were from low (incompressible) to high (supersonic).

In all the projects, Direct Numerical Simulations (DNS) and Large–Eddy Simulations (LES) were carried out with the goal of pushing the relevant Reynolds number to as high a value as currently feasible with available supercomputers. The DNS are based on solving the complete Navier–Stokes equations with no further assumptions other than those made for deriving these equations. The LES require subgrid–scale models. For LES, the grid spacing is such that only the larger scales are resolved directly by the computational grid. Scales smaller than the grid have to be modeled.

In all the projects, the underlying computational model was "spatial." Thus, the structures evolving in the transitional and turbulent flows could develop (grow or decay) not only in time, but also in the spatial (downstream) direction, as is the case in realistic laboratory experiments or in free flight. This spatial model is in contrast to the so-called "temporal" model, for which spatial (downstream) periodicity is assumed and which therefore introduces assumptions that are not realistic for many situations. The temporal model allows for short computational domains and thus considerably reduces the computational demands and, in particular, the size of the data files produced by the numerical simulations.

The realistic spatial simulation model, on the other hand, lead to considerably higher computational complexity because of the typically much larger (in the downstream direction) computational domains required and because of the difficulties associated with providing and implementing proper inflow and outflow boundary conditions. As a consequence of employing the spatial model, considerably more time and effort were necessary for code development. The numerical methods had to be very accurate and efficient for simulations with such large grid sizes to be at all feasible on supercomputers. These efficiency and accuracy requirements, together with the difficulties associated with inflow and outflow conditions, required extensive testing in the development phase of the computer code. For this reason, adequate pre–processing capabilities has been essential for effective utilization of available supercomputing resources. The high–performance workstations acquired (Power Challenges in connection with the Indy's) have met our pre–processing needs. The pre–processing capability of the workstations has enabled us to do all of our pre–processing locally. This has helped to relieve the network and to unclog the remote

supercomputers. After all, the supercomputers are best utilized for number crunching, and using it for code development purposes, which can be done more efficiently on considerably less expensive machines, is in fact a waste of supercomputing resources.

In addition, post–processing of the massive amount of data that results from our simulations had been very cumbersome (if possible at all) when carried out remotely at the supercomputing centers. Even attempting it had been wasteful of supercomputing resources. Our post–processing needs have been met more efficiently and cost effectively on the powerful high–performance workstations. The flows that we were studying were dominated by the generation and evolution of coherent turbulent structures. These three–dimensional, non–periodic structures cover a wide range of spatial and temporal scales. Due to their non–periodic nature, their dynamics cannot be analyzed by means of Fourier transforms. Therefore, detailed investigations of the space–time evolution of the physical flow field was essential to gaining an understanding of the dynamics and the underlying physics of the turbulent structures. This had important implications for the post–processing of the data generated in our numerical simulations.

Since it is the rapid changes of the flow field with time that was important, the most revealing information concerning the dynamical behavior of the flow structures was obtained by scrutinizing animations of the unsteady data, rather than snapshots of the flow depicting its state at one instant in time. In order to generate these animations at every time step, the data first had to be read from disk into memory. Then the data were processed to extract useful information, e.g., to compute level surfaces of flow variables, particle traces, kinetic energy levels, entropy distributions, etc. Finally, the processed data were sent to the graphics processor for display on the screen. This whole process was then repeated for the next time step. Typical data sets required approximately 50 MB of disk space (and 50 MB of memory) per time step, where a meaningful animation of a non–periodic flow required several hundred time steps. These post–processing demands are in contrast to "mainstream" CFD applications, where only a steady–state mean flow is computed and visualized.

For truly interactive time–dependent graphics processing, the powerful graphics workstations from Silicon Graphics (Power Onyx and Power Indigo) in combination with the 36–GB hard drive array with high–speed disk I/O capable of simultaneously reading from multiple individual disks have proven to be vital. The acquired equipment has allowed us to cut the time required to generate a time–dependent animation from a day down to several minutes. The gains in speed resulted from two factors: (1) The use of disk array (redundant arrays of independent disks) technology has increased the data transfer rate from the disk by a factor of up to 10. (2) The use of multiple processors has increased the rate of data processing once the data are in memory. An advantage of the acquired Onyx system is that additional processors can be added as processing demands increase with increased computing powers of new supercomputers. The resulting speedup has resulted in a qualitative change in our post–processing: The shorter turn–around time has enabled us to do truly interactive graphics processing.